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Field study of the performance for a solar water heating system with MHPA-FPCs

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Abstract

In this paper, the thermal performance of a large-scale solar water heating system (SWHS) with flat plate collectors based on micro heat pipe array (MHPA-FPCs) is presented. The system was built to provide hot water for dishwashing in a university cafeteria in Beijing, China. The thermal performance tests for the system were conducted at different conditions.The field trial data were analyzed from the aspects of different solar irradiation, ambient temperature and initial temperatures in water tank. Test results show that more solar irradiation, higher ambient air temperature and lower initial water temperature could achieve higher system efficiency. The daily system efficiency could reach 62% with large solar irradiation and small temperature between the collectors' temperature and the ambient temperature. Under different conditions, the average system efficiency approached 50%.The test results present excellent characteristics for the large-scale SWHS with MHPA-FPCs. A large number of worthy experimental data are got from this paper, which can serve as an important basis for understanding the field operation of large-scale novel MHPA-FPC SWHS.

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*Keywords:*Solar water heating system; MHPA-FPCs; Field study; Large-scale; Thermal performance

1. Introduction

Solar water heating systems (SWHSs) are widely applied in both domestic and commercial sectors. With huge amount of solar irradiation of about 50×10^{15} MJ received each year[1], China has become one of the top countries in the world in using solar energy. Study on the performance of SWHS has profound significances and broad market prospects, especially in China.

With the large-scale popularization of SWHSs, many studies focused on evaluating the performance of SWHSs. A number of studies have conducted experimental investigations on the thermal performance of SWHSs under real

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weather conditions [2- 6]. Other researchers have achieved a long-term performance investigation or optimization of SWHS by developing a simulation model by TRNSYS program [7- 9]. However, large-scale SWHS in actual operation has not been systematically evaluated. As shown in Fig.1, MHPA-FPC is a novel type of flat plate collector [10]. Compared with the traditional flat plate collectors (FPC), the MHPA-FPC has some advantages, high heat transfer capability, simple processing technology, low cost and high pressure resistant. In the previous studies, thermal performance tests of the MHPA, MHPA-FPC, and household scale SWHS with MHPA-FPC have been conducted. The experiments carried by Zhao YH [11] has showed that the maximum heat flux of MHPA could reach 102 $W \cdot cm^{-2}$. Deng YC[12,13] has proven the excellent isothermal ability and quick thermal respond speed of MHPA. Different influence parameters were tested to improve the performance of MHPA-FPC. Then the performance of MHPA-FPC was investigated following the Chinese standard GB/T4271-2007. It has been found that the maximum instantaneous efficiency could be 80%, and the heat loss factor was -4.72. To specify the performance MHPA-FPC, Yuechao Deng, Wei Wang [14]presented the whole year performance of a household scale SWHS with MHPA-FPC under testing conditions. The annual average system efficiency was found to be 58.29%.

In this paper, the field study on a large-scale SWHS with MHPA-FPCs in Beijing, China is presented. The performance of the test system under different conditions was investigated to provide information for design and operation the large-scale SWHS based on MHPA-FPC.

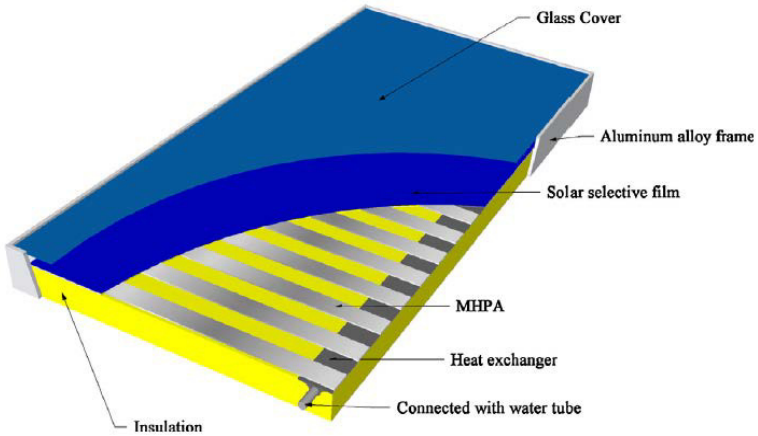


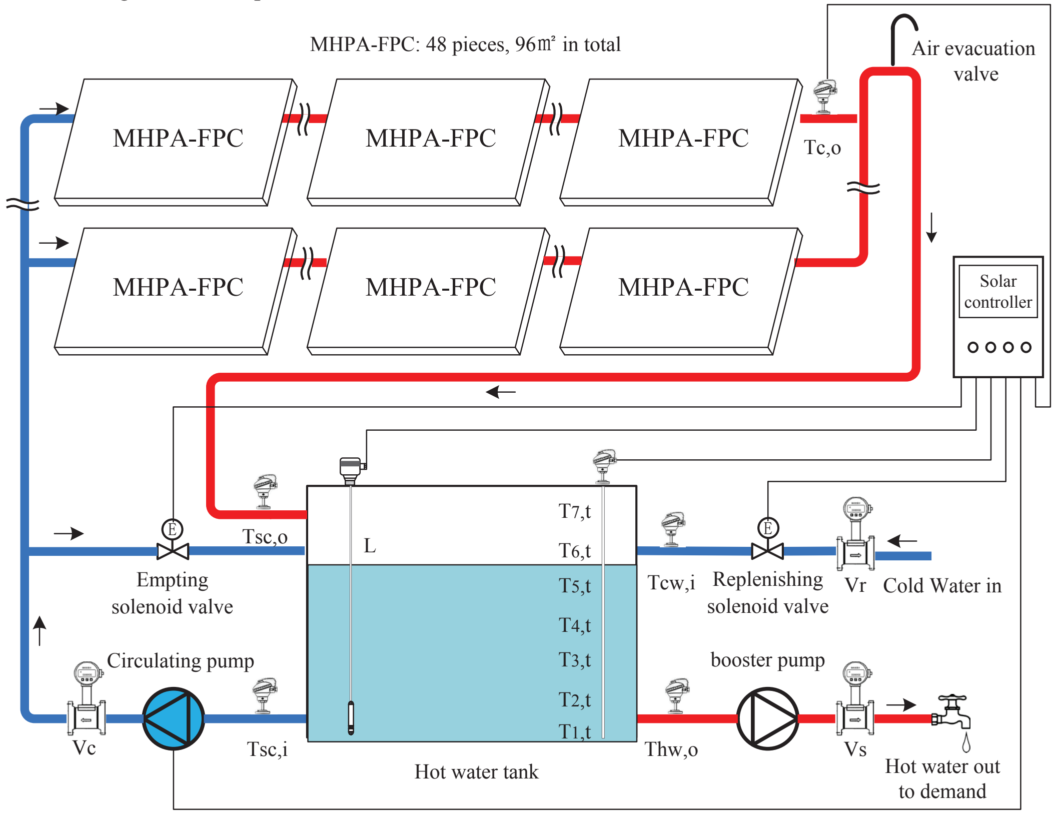
Fig.1. The configuration of MHPA-FPC [14]

2. Test system

2.1. System introduction

The test system was a forced circulation SWHS with MHPA-FPCs, which was built to provide hot water for dishwashing in a university cafeteria in Beijing, China(latitude 39° 52′ N and longitude 116° 28′ E), as shown in Fig.2. It consisted of a 5 m^3 water tank, 48 pieces of MHPA-FPCs with solar collection area 2m^2 for each piece, a water circulating pump, a hot water booster pump, two solenoid valves and control unit. The MHPA-FPCs were installed south facing and inclined at 45° , 8 collectors hooked up in series, 6 rows in total. All pipe fittings were insulated to reduce heat loss.

The SWHS was equipped with a solar controller which had relay inputs to control the operation of the pumps as well as opening and shutting the solenoid valves. The water circulating pump was controlled by temperature difference between temperature at the collector outlet and temperature in the bottom of water tank. When the temperature difference was more than 7℃,the water circulating pump started. Then the pump operated until the temperature difference dropped to 3℃.When the circulation stopped, cycle pipes were empty through a solenoid valve, preventing the piping congelation. And the operation of cold water supply was controlled by the water level and water temperature. There were two situations: the water volume was less than the set value, or the water temperature is higher than set point.



$T_{c,o}$ is water temperature at the collector outlet, ℃; $T_{sc,i}$ and $T_{sc,o}$ are water temperatures inlet and outlet to the solar collector array, ℃; $T_{cw,i}$ is cold water temperature, ℃; $T_{hw,o}$ is hot water supply temperature, ℃; V_c, V_r, V_s are water volume flow rate of circulation, cold water replenishment and hot water supplement, $m^3 \cdot h^{-1}$; L is water level, m; $T_{1,t}$-$T_{7,t}$ are water temperature at the different level of tank, ℃.

Fig.2. Schematic diagram of the SWHS

2.2. Test parameters and instruments

To investigate the performance of the SWHS, the parameters measured include the following:

(1) Meteorological parameters: solar irradiance, ambient air temperature.

(2) Operating parameters: $T_{a,tank}$, $T_{c,o}$, $T_{sc,i}$, $T_{sc,o}$, $T_{cw,i}$, $T_{hw,o}$, V_c, V_r, V_s, L

The water temperature was measured by PT100 thermal resistors with an accuracy of ±0.3 °C. The volumetric flow rate of the water was measured using turbine flow meters(LWGY-25C10S，LWGY-25C20S) with an error range of ±15%. A pressure transmitter (HT709) with an accuracy of 0.25% was used to measure water level of tank. The test data were recorded by a data acquisition system every 10 seconds. And an automatic weather station (TYD-ZS2) was used to collect meteorological data. Weather data were logged at 1 min intervals. The position of the thermocouple sensors and the flow sensors were shown in Fig.1.

2.3. Data reduction

Data presented in the paper is obtained from operating data of the system in 2012. Several influence factors were used to analyze the performance of the MHPA-FPC SWHS. They consisted of solar irradiation, ambient air temperature, initial temperature in water tank. The test data recorded from 8:00 to 16:00.

Based on the measured parameters, the effective heat gain by the solar collector is given as:

$$Q_c = \int \rho V_c C_p \left(T_{sc,i} - T_{sc,o}\right) dt \tag{1}$$

The system efficiency was calculated as:

$$\eta_s = \frac{Q_c}{A_c \int I_t dt} \tag{2}$$

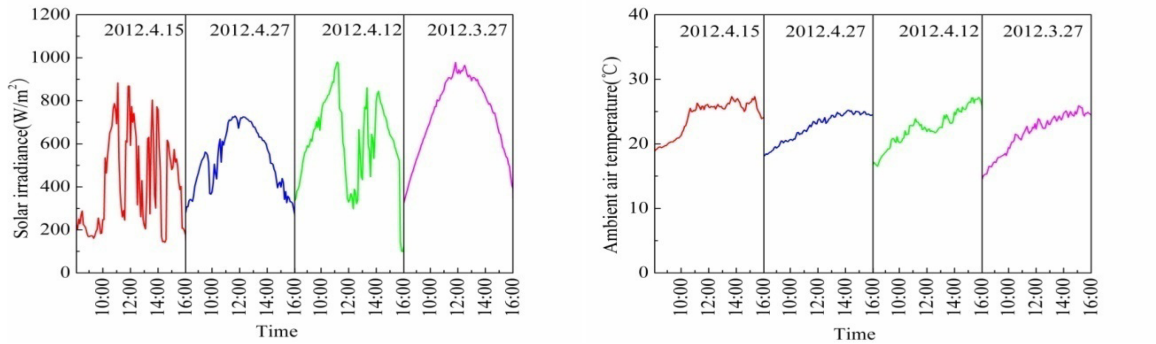
Where Q_c is the effective heat gain by the solar collector, MJ; η_s is system efficiency; V_c is water volume flow rate of the circulation, $m^3 \cdot h^{-1}$; C_p is water specific heat, $J \cdot kg^{-1} \cdot K^{-1}$; $T_{sc,i}$ and $T_{sc,o}$ are water temperature at inlet to and outlet from the solar collector array, ℃; A_c is aperture area of the solar collector, m^2; I_t is solar irradiance, $W \cdot m^{-2}$.

3. Results and discussions

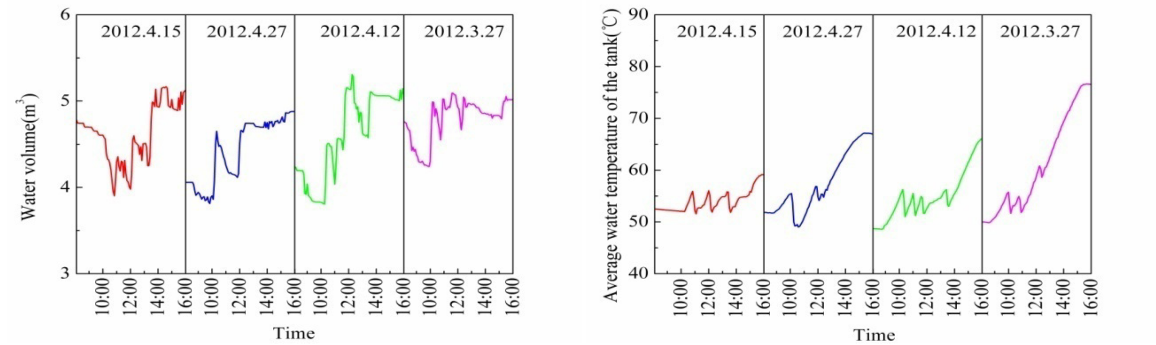
The thermal performance of the test system under different conditions was investigated. The test data were analyzed from the aspects of different solar irradiation, ambient air temperature and initial water temperatures.

3.1. Solar irradiation variation

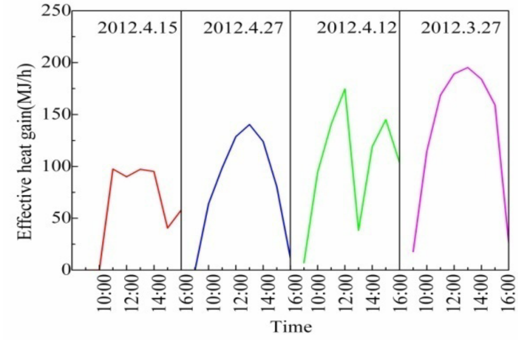
Fig. 3 presents the data of four typical days with solar irradiation variation. They were chosen from 2012.4.15, 2012.4.27, 2012.4.12 and 2012.3.27. Fig. 3a shows plots of solar irradiance during four days. The total daily solar irradiation were 12, 15, 17 and 21MJm$^{-2} \cdot$d^{-1}, respectively.



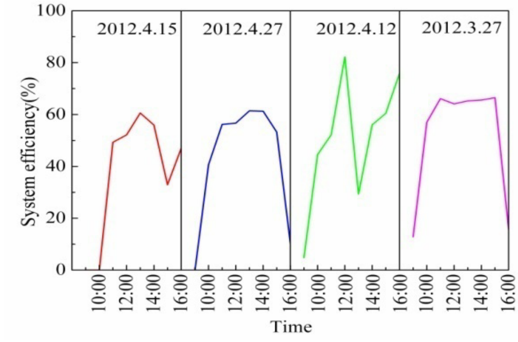
(a)Solar irradiance (b) Ambient air temperature



(c) Water volume (d) Average water temperature



(e)Effective heat gain



(f) System efficiency

Fig.3.Test data in typical days with solar irradiation variation

Fig. 3b shows plots of ambient air temperature. The daily average temperatures were 24.2, 22.6, 22.5 and 21.7℃, respectively. Fig. 3c shows plots of daily variation in water volume in the tank, which were caused by the hot water draw-off or cold water supply. The volumes decreased rapidly from 8:00 to 10:00 and from11:00 to 13:00, which had obvious characteristics according to meal time. There are some sharp increases at the end of testing, which was caused by the circulating. When the circulating pump stopped, water in cycle pipes returned to water tank.

Fig. 3d describes the average water temperature variation. The water temperatures at 8:00 approached 50℃. Then the temperatures increased with the increase of solar irradiation and ambient temperature. As the control program, the temperatures rose to 55℃ lead to cold water supplement until it decreased to 50℃. Then the water temperature increased over 55℃ in the afternoon because water volume had reached to the largest water volume.

Fig. 3e and Fig. 3f present the variation of the hourly effective heat gain and system efficiency in the typical days. The solar irradiation trends on April 27 and March 27 were similar to each other, while the peaks were 729 and 978 MJ·m^{-2}. The hourly system efficiencies on March 27 were higher than April 27. As the solar irradiation on April 15 varied dramatically, the hourly system efficiencies were lower than other days even the hourly solar irradiation was larger. In the four typical days, the daily system efficiencies were 44%, 47%, 52% and 56%, respectively. Results show that more solar irradiation could achieve higher system efficiency. And the continuity of solar irradiance is beneficial to improving the effective heat gain.

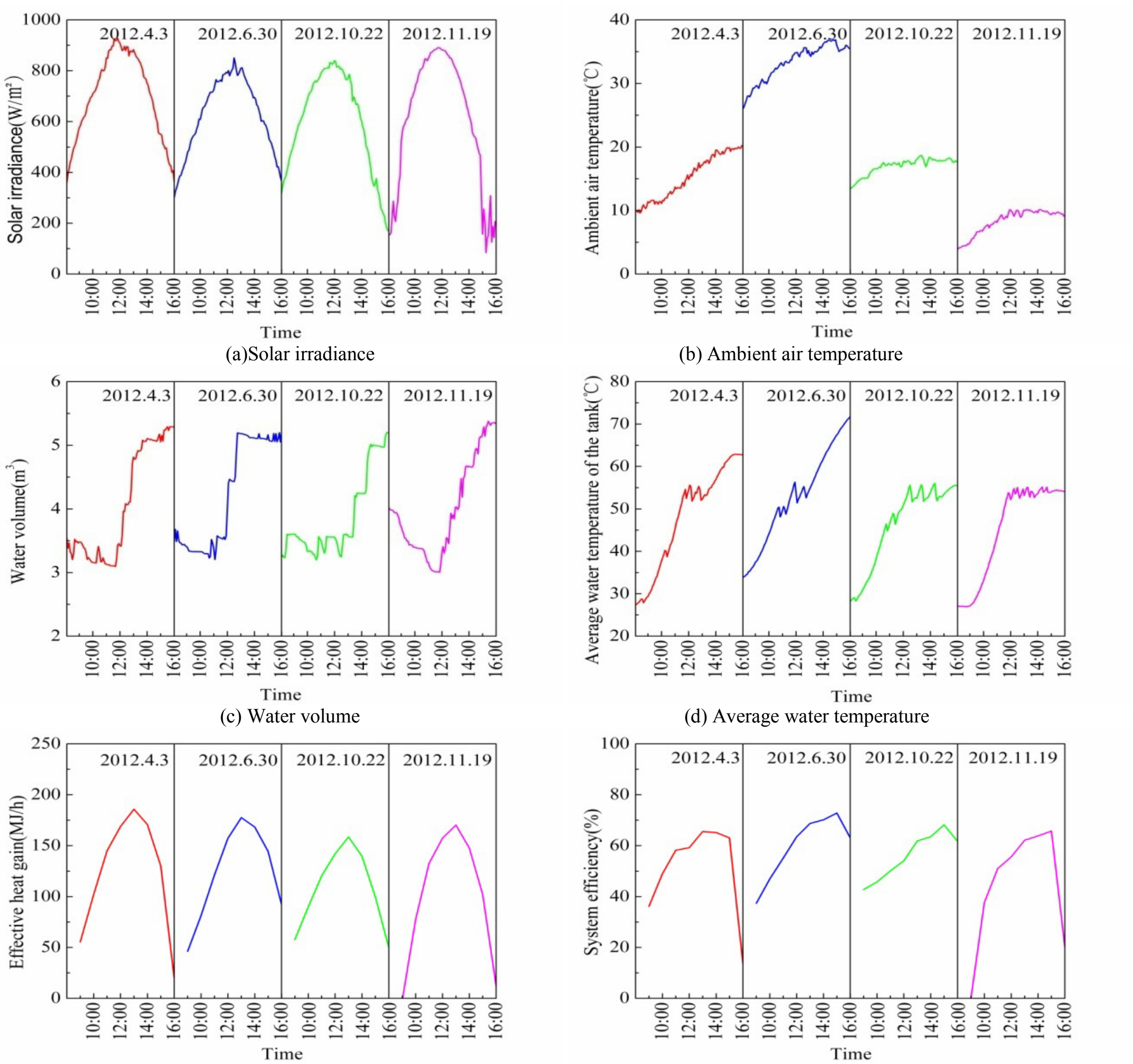
3.2. Ambient air temperature variation

Fig. 4 shows plots of daily variation in four typical days from different seasons. They were 2012.4.3, 2012.6.30, 2012.10.22 and 2012.11.19. Fig. 4b shows the fluctuations of ambient air temperature. They were found to be 9.6℃ to 20.2℃, 26.0℃ to 36.9℃, 13.4℃ to 18.7℃and 3.8℃ to 10.1℃, respectively. And the daily average temperatures were 15.2℃, 33.3℃, 17.0℃, and 8.3℃, respectively.

The plots of irradiance and water volume in typical days are shown in Fig. 4a and c. The curves of the solar irradiation all presented parabolic shapes. Total solar irradiation were 20, 18, 17, 17 MJ·m-2·d-1, respectively. In Fig. 4d, the initial water temperatures at 8:00 are 27.3, 33.9, 28.0 and 26.8℃. Then, the circulating pump operated, the water temperatures increased linearly with the increase of solar irradiation. The temperatures dropped several times then rose over 55℃for the same reason explained above.

Fig. 4e presents the variation of the hourly effective heat gain in four days. The hourly effective heat gains kept increasing from 8:00 to 12:00. The peaks appeared at 12:00 were 186, 177, 158, and 170 MJ, respectively. Then the hourly effective heat gains gradually decreased due to the decrease of solar irradiation and increase of heat loss caused by the increase of differences between the collectors' temperature and the ambient temperature. In four typical days, the daily effective heat gains were 978, 988, 857 and 799 MJ, respectively. Data on June 30, October 22 and November 19 showed that the daily effective heat gains increase with the temperature increased. And as the higher irradiation, the daily effective heat gain on April 3 was much higher than October 22, which ambient temperature was similar.

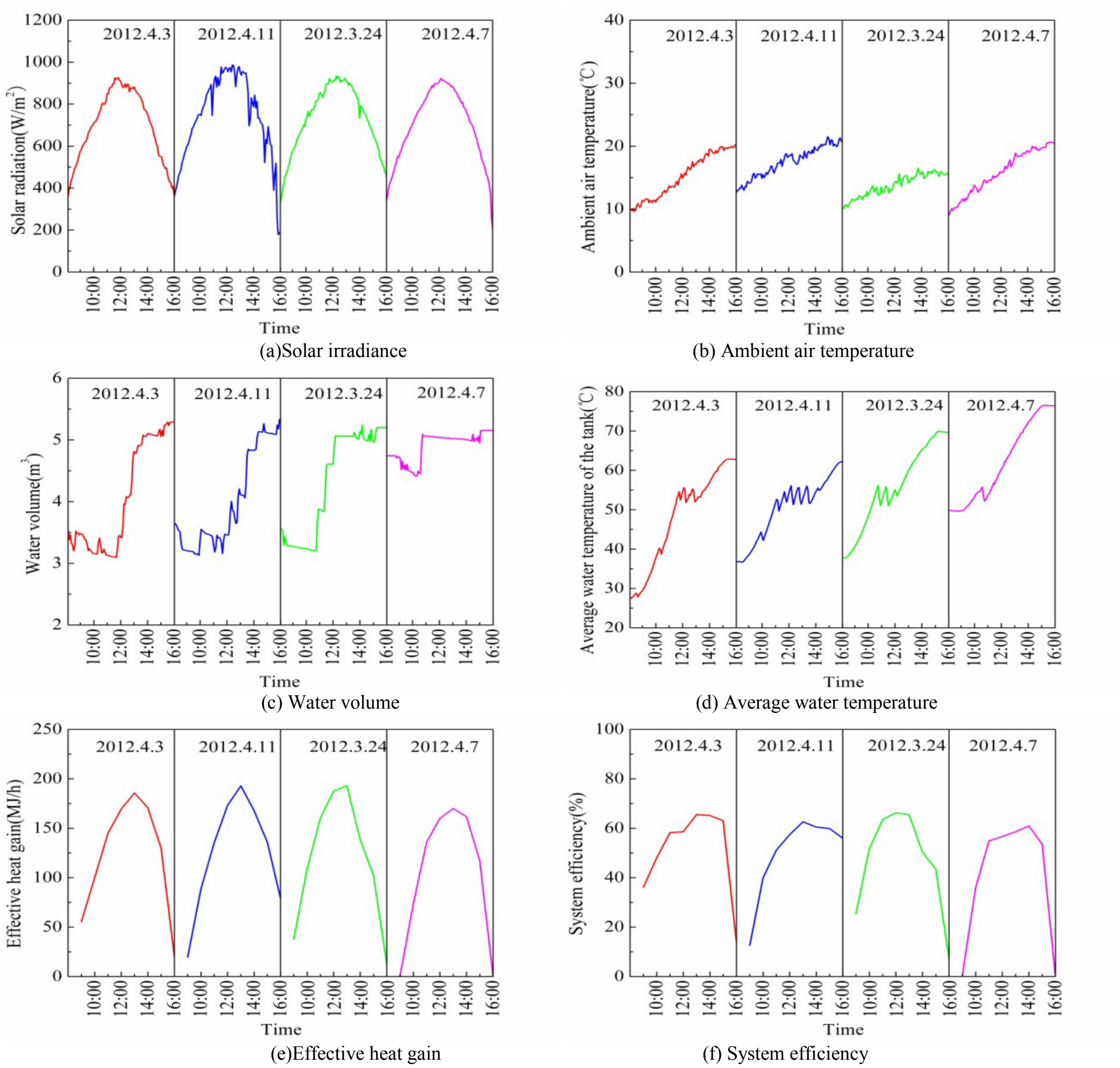
Fig. 5f describes the hourly system thermal efficiency. The daily average system efficiencies of the typical days were 54%, 62%, 56% and 52%, respectively. The daily average system efficiency on November 19 was the minimum value due to a large heat loss caused by low ambient temperature. While the maximum value of daily average system efficiency was 62% on June 30. On the other two days, the daily average system efficiencies were 55%, approximately. This shows that increase of temperature difference between the collectors' temperature and the ambient temperature will enlarge heat loss, which will lead to the system efficiency reducing.



(a)Solar irradiance (b) Ambient air temperature
(c) Water volume (d) Average water temperature
(e)Effective heat gain (f) System efficiency

Fig.4.Test data in typical days with ambient air temperature variation

3.3. Initial temperatures in water tank variation



(a)Solar irradiance (b) Ambient air temperature

(c) Water volume (d) Average water temperature

(e)Effective heat gain (f) System efficiency

Fig.5.Test data in typical days with Initial temperatures in water tank variation

Four typical days with different initial temperatures in water tank are shown in Fig. 5. They are 2012.4.3, 2012.4.11, 2012.3.24 and 2012.4.7. Fig. 5d shows the fluctuations of water temperature. The initial temperatures in water tank were 27.3, 36.9, 37.8 and 50.0℃ at 8:00. Fig. 5a and b show plots of solar irradiance and ambient air temperature.The solar irradiation and average ambient air temperature were 20 MJ and 15.2℃, 21 MJ and 17.5℃, 21 MJ and 13.8℃, 20 MJ and 15.8℃. Fig. 5c shows the fluctuations of water volume.

Fig. 5e and f present the variation of hourly effective heat gain and system efficiency. The daily effective heat gains of the typical days were 981, 984, 924 and 808 MJ, while the daily average system efficiencies were 55%, 52%, 50% and 45%, respectively. The data showed that the daily average system efficiency drops with the rise of initial temperature. It is due to the decrease of temperature difference between water temperature and temperature of collectors reducing the heat gain by collectors. The initial temperature in the tank has a significant influence on the daily efficiency of the system.

4. Conclusions

In this paper, a large-scale SWHS with MHPA-FPCs in actual operation was test to further investigate the performance of SWHS based on MHPA-FPC. The test data were analyzed from the aspects of different solar irradiation, ambient air temperature and initial temperatures in water tank. Results show that (1) more solar irradiation could achieve higher system efficiency. When the solar irradiation reached 21MJ $MJm^{-2}\cdot d^{-1}$, the daily system efficiency could be 56%. The daily effective heat gain was nearly 1050MJ. (2) Under different ambient air temperature conditions, the maximum value of daily average system efficiency was 62% with small difference between the collectors' temperature and the ambient temperature. While the daily average system efficiencies were nearly 55% on other days. (3)The initial temperature in the tank has a significant influence on the daily efficiency of the system. The increase of temperature difference between water temperature and temperature of collectors will increase the heat gain by collectors. Compare with other days, the daily system efficiency could reach 55% by the initial temperature of 27℃. The test results present excellent characteristics for the large-scale SWHS with MHPA-FPCs under different conditions.

Acknowledgements

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